# Height Profile of the Sq Current in the Midlatitude Ionosphere


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# *Height Profile of the Sq Current in the Midlatitude Ionosphere*

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*Abstract*: Under the assumption that the ionospheric Sq current flows only in the horizontal direction, the height distribution of the current intensity is calculated as a function of the direction of an electrostatic field, for a location at 20° of the geomagnetic latitude. The result shows that the height profile of the current is subtly depending on the direction of an electric field; the maximum current being sometimes near the E-peak, and sometimes in the region between 120 and 130 km. Remarks are made on the change in the magnetic field, detectable by a rocket-borne magnetometer, as it passes through the region where currents flow.

## 1. Introduction

Since the direct detection of the electric current in the dynamo region of the ionosphere responsible for the geomagnetic Sq variation was first succeeded in 1950 by means of a rocket-borne magnetometer (Maple, Bowen, and Singer, 1950), attempts have been repeatedly made to illustrate the height distribution of the Sq current at or near the equator (Singer, Maple, and Bowen, 1952; Cahill and Van Allen, 1958; Cahill, 1959a; Maynard and Cahill, 1965a, b), at midlatitudes (Heppner, Stolarik, and Meredith, 1958; Burrows and Hall, 1965; Davis, Stolarik, and Heppner, 1965), and at a high latitude (Cahill, 1959b). Although the circumstances at the equator are somewhat different from those at middle or high latitudes, it is generally agreeded that a major part of the Sq current flows in the region between about the 100km- and 130km-levels. The current intensity attains to its maximum, in general, at a height near the E-peak, but sometimes shows two maxima, one being near the E-peak and the other in the region between 120 and 130 km.

The experiments so far undertaken, however, were concerned with the increasing departure of the total magnetic force from that expected from the dipole field with a correction for a local anomaly. The change $\Delta F$ in the total force detectable by a rocket-borne magnetometer when it penetrates through a horizontal current sheet with the current density $J$ is approximately given by $4\pi J \cos I \sin \theta$, where $I$ denotes a dip angle and $\theta$ is a directional angle of the current measured eastward from the magnetic north. Therefore, when the current direction $\theta$ is not known, it is not easy to deduce the current intensity from the measured change $\Delta F$ in the total field; it gives an information only about the east-west component of the current. A further complication arises from the fact that the current direction varies considerably with increasing height.

On the basis of the vertical distribution of the electrical conductivity estimated theoretically, the height variation of the current vector at a midlatitude is described in this paper as the function of the direction of a uniform electrostatic field. A suggestion is then made on various possible manners in which the change in the total force is detected by a rocket-borne magnetometer as it passes through the current region.

## 2. Electrical conductivity

At middle and low latitudes, electric currents may be considered to flow horizontally in the conductive region of the ionosphere. Assuming that the vertical component of the current is absent, Hirono (1952) has given for the horizontal components of the current the well-known equations,

$$\left.\begin{aligned} i_x &= \sigma_{xx} E_x + \sigma_{xy} E_y, \\ i_y &= -\sigma_{xy} E_x + \sigma_{xy} E_y, \end{aligned}\right\} \tag{1}$$

where $E_x$ and $E_y$ are the components of an electrostatic field, and the coefficients are defined as

$$\sigma_{xx} = \frac{\sigma_0 \sigma_1}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I,},$$

$$\sigma_{xy} = \frac{\sigma_0 \sigma_2 \sin I}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I}, \tag{2}$$

and

$$\sigma_{yy} = \frac{\sigma_0 \sigma_1 \sin^2 I + (\sigma_1^2 + \sigma_2^2) \cos^2 I}{\sigma_0 \sin^2 I + \sigma_1 \cos^2 I}.$$

In the above definitions, we denote by $\sigma_0$ the electrical conductivity parallel to the magnetic field, by $\sigma_1$ the Pedersen conductivity, and by $\sigma_2$ the Hall conductivity. As the electrical conductivity depends upon the concentrations of electrons and various ions, the intensity of magnetic field, and upon the atmospheric pressure, it changes with height as well as with time and location. In the actual condition of the earth's ionosphere in daytime, however, the conductivity is almost proportional to the electron density (Kamiyama, 1959). Hence, it is convenient to show the vertical distribution of the conductivity for a given location with assuming a constant electron density, because a modification is needed only for an actual vertical profile of the electron density.

The results for $\sigma_{xx}$, $\sigma_{xy}$ and $\sigma_{yy}$ at 20° of geomagnetic latitude ($I=36°$) for the constant electron density, $n_e = 1\times10^5 \mathrm{cm}^{-3}$, calculated on the basis of the values for $\sigma_0$, $\sigma_1$, and $\sigma_2$ (Kamiyama, 1965) are shown in Fig. 1 as the function of altitude. Referring to an actual distribution of $n_e$, it is inferred from this figure that the maxima of $\sigma_{xx}$ and $\sigma_{yy}$ are expected at heights between 120 and 130 km, while $\sigma_{xy}$ attains to its maximum at the E-peak.

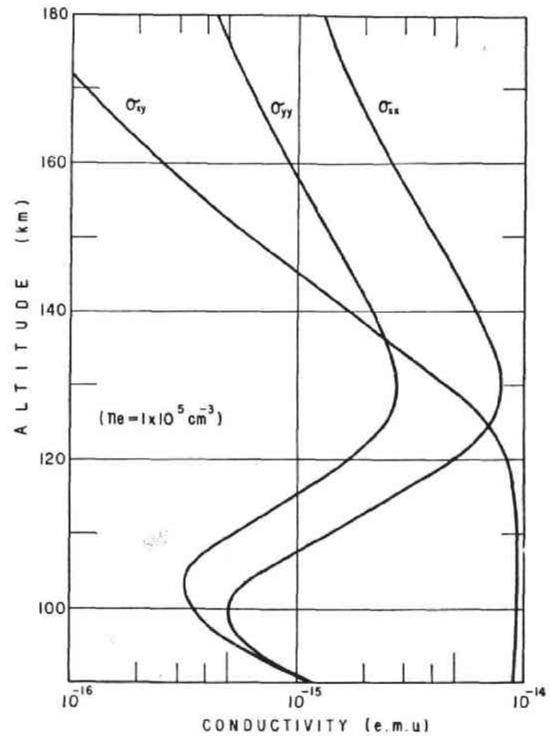


Fig. 1 Tensor components of horizontal electrical conductivity as the function of altitude for a constant electron density, $n_e = 1 \times 10^5 \mathrm{cm}^{-3}$.

## 3. Electric currents

A current changes subtly its intensity and direction with height due to the changes in the tensor components of the conductivity. Assuming a uniform electrostatic field $\boldsymbol{E}$ throughout the region concerned, the southward and eastward components of currents are calculated as shown in Figs. 2a and 2b as the functions of altitude. The negative direction (northward or westward) of the components are drawn as dashed line. The directions of an imposed electric field are indicated by numerals marked on the curves: 1, eastward field; 2, south-eastward; 3, southward; and 4, south-westward field. When the direction of an electric field is reversed, currents flow in the opposite directions to those shown in the figures. We can point out from these figures the followings; (1) When the direction of an electric field is eastward, the maximum of the NS-component of the current lies at the E-peak, whereas its EW-component may attain to its maximum at a height between 120 and 130 km.

(2) When the field is south-eastward, the maxima of the both components of the current are found near the E-peak. It is also noted here that the NS-component extends to a considerable thickness, while there is a reversal in the direction of the EW-component at about 135 km.

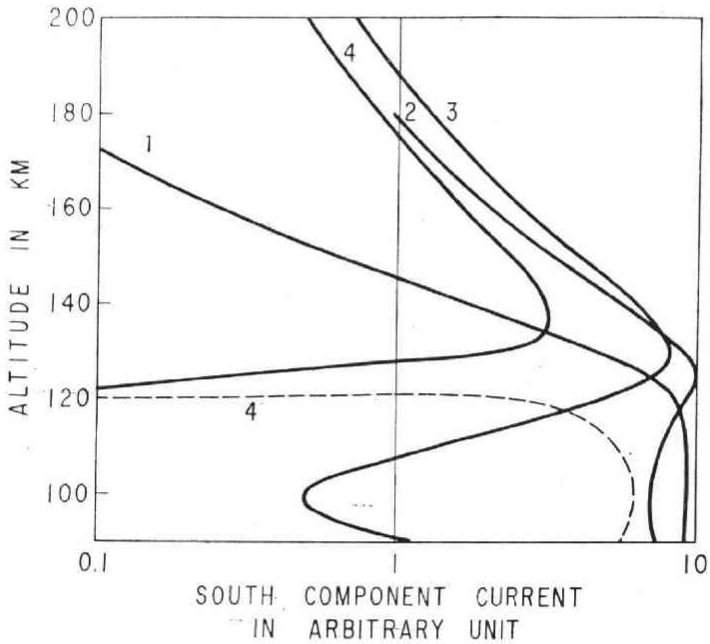


Fig. 2a Southward component of the electric current. Negative (northward) current is drawn as dashed line. Numerals shown on the curves indicate the direction of an imposed electrostatic field: 1, Eastward field; 2, South-eastward; 3, Southward; 4, South-westward.

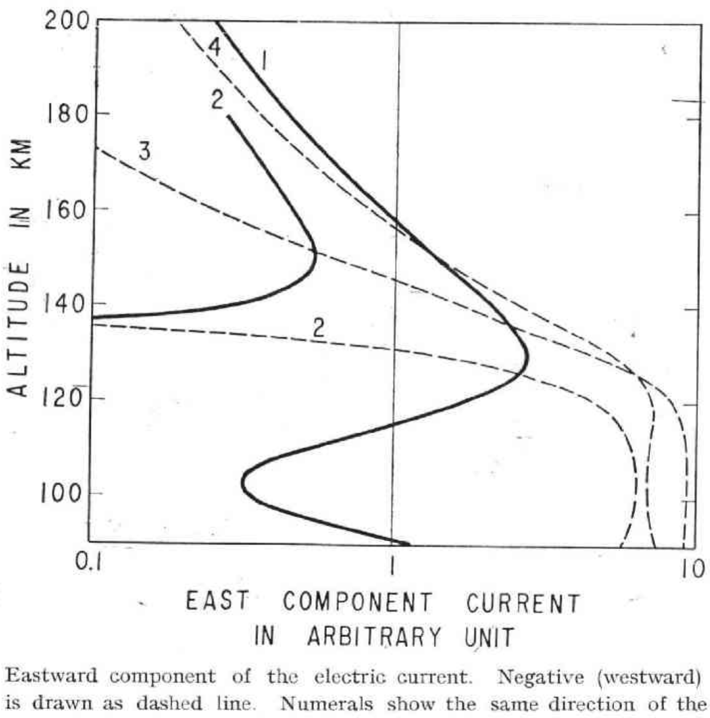


Fig. 2b Eastward component of the electric current. Negative (westward) current is drawn as dashed line. Numerals show the same direction of the electrostatic field as in Fig. 2a.

(3) When the field is southward, the maximum of the EW-component is found near the E-peak, whereas the maximum of the NS-component is in the region between 120 and 130 km.
(4) When the field is directed toward south-west, the maxima of the both components of the currents are found near the E-peak, and a reversal of the direction of the NS-component appears at about 120 km.

Although the vertical distribution of the current intensity will be inferred from these two components, it shows a subtle variation with height depending on the direction of the field. Being based on the results given in Figs. 2a and 2b, the relation between the field vector and the current vector are shown in Fig. 3 at some selected altitudes. The vector, $\boldsymbol{A}, \boldsymbol{B}$, and $\boldsymbol{C}$ are the currents at the altitudes of 110, 130, and 150 km, respectively. It may be said that in the northern hemisphere, in general, the current direction precedes clockwise the field direction by several tens degrees. The current intensity does not necessarily attain to its maximum at the E-peak, but sometimes at a height between 120 and 130km. In a special case in which the field is directing eastward and the electron density shows a sharp peak in the E layer, two maxima of the EW-component of the current could be expected, one being at the E-peak and the other in the region around 125 km.

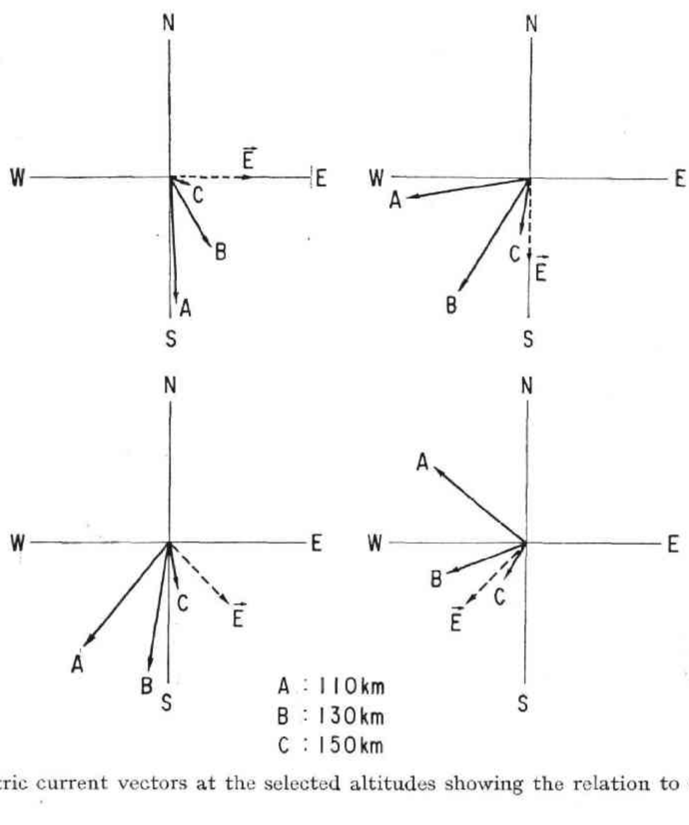


Fig. 3 Electric current vectors at the selected altitudes showing the relation to electric field.

## 4. Magnetic field as detected by a rocket-borne magnetometer

The deviations in the total magnetic force from that of the dipole field with a correction for a local anomaly have so far been measured by rocket-borne magnetometers to detect the current sheet in the ionosphere. As is well known, a uniform infinite current sheet on which the current intensity per unit width is $J$ produces a magnetic field $2\pi J$ parallel to the current plane but perpendicular to the current. Hence, the change in the total force detected by a rocket-borne magnetometer as it penetrates the current sheet is given by $4\pi J \cos I \sin\theta$, $\theta$ being the angle between the current direction and the north. When a magnetometer is at a height, $h$ in a current region with a finite thickness, the detectable deviation from the dipole field is given by $2\pi \cos I \times\left(\int_h^\infty j \sin\theta\,\mathrm{dh} - \int_0^h j \sin\theta\,\mathrm{dh}\right)$, where $j$ is the current density. Thus, from the height integrations of the EW-component of currents, we can illustrate in Fig. 4 the manners in which the deviation from the dipole field changes as a rocket passes through a current region, for the several representative cases. It is seen from the figure in which the directions of the electrostatic field are indicated on each of the curves, that the manner is considerably depending on the direction of an imposed electric field. This

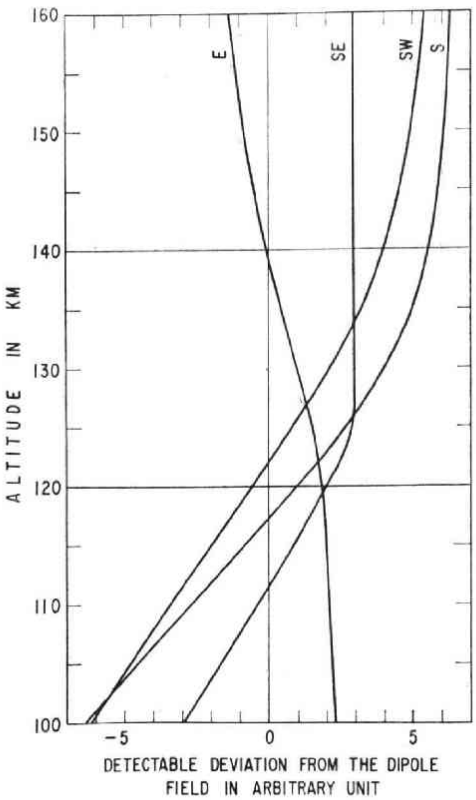


Fig. 4 Various manners in which the deviation from the total magnetic force of a dipole field is detected by a rocket-borne magnetometer as it passes through the current region.

means that the change detectable by a rocket-borne magnetometer may be remarkably characterized by a location and a local time.

## 5. Concluding remarks

Based on the vertical distribution of the electrical conductivity estimated theoretically, the height variation of the current vector is given as the function of the direction of an imposed electrostatic field which is assumed to be constant throughout the region concerned. We have seen that the profile of the Sq current in the ionosphere is subtly depending upon the direction of the field. The result is suggesting that the measurement by a rocket-borne magnetometer of the three components of the change in the geomagnetic field provides us a much more useful information about the ionospheric current.

In this paper, we have assumed a constant electrostatic field. It is known, however, that winds are not uniform in the ionospheric region; the direction and the speed of winds being changed rapidly with increasing height. In such a case, the total electric field at a point is given by $\boldsymbol{E}(\text{static})+V\times\boldsymbol{B}$, where $V$ is a local wind vector. Hence, the distribution of the currents may be strongly affected by a local wind. Then the combined experiment measuring the vertical distributions of the electron density, the wind velocity, and the changes in the three component (or at least in the two horizontal components) of the magnetic field is greatly needed in order to make a detailed study of the dynamo current in the ionosphere.

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